

## **Two-phased inventory of standing volume in mountain forests with the use of aerial photographs**

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### **ABSTRACT**

This study aimed to elaborate and develop the existing methods used in inventorying lowland forest and adapt them for mountainous forests.

The inventory of mountain forests with the use of CIR aerial photographs in this study relied on the implementation of the 3D (three-dimensional) methods and it was characterised by two phases. In the 1<sup>st</sup> phase the auxiliary variables (e.g. crown cover, height of dominant trees, density) were measured on the aerial photographs (355 circular plots). Variable of interest (standing volume) was recorded during the terrestrial survey on the corresponding ground sample plots. A statistical relationship was established between the variable of interest and the auxiliary variables by means of multiple regressions. In the 2<sup>nd</sup> phase selected auxiliary variables were measured on the enlarged set of 2772 plots on the aerial photographs only. The variable of interest (standing volume) was computed for the whole forest area by using the regression model developed in the 1<sup>st</sup> phase and the aid of the variables measured in the 2<sup>nd</sup> phase.

### **KEY WORDS**

aerial sample plot, CIR, forest inventory, ground sample plot, Stołowe Mountains National Park

### **INTRODUCTION**

Forest inventory as the key planning and controlling tool in forestry is based on the data collection, which can be separated in 1) (measured) primary data, 2) (calculated) secondary data and 3) estimated data and results in information about the forest stands attributes such as: tree species, tree species composition, breast height diameter (DBH), tree height, number of trees, basal area, age and more importantly the estimation of standing volume and volume increment. The process of forest inventory which is carried out to provide such data mainly is conducted by using traditional methods,

which means all the necessary primary data are measured on the ground (Akca et al. 1996).

Traditional way of forest inventories appears to be quite time consuming, plus requires a huge amount of human labour and culminates in high costs. Therefore the implementation of new technologies combined with the traditional way of forest inventory could be more promising in reducing the time for accomplishing such tasks and simultaneously the costs, thus increasing the efficiency of forest management.

The inventory of mountain forests with the use of aerial photographs relies on the implementation the 3D (three-dimensional) methods. This is much more rele-

vant in mountain forests where often aerial photographs have been used to reduce the effort of data collection. By increasing the technical standards, especially in computer science during the last decades, 3D methods can be implemented in such processes, however this does not substitute completely the traditional ground-based forest inventories. There are needed ground-based inventory data sets to compare with the aerial data in order to determine the accuracy e.g. standing volume estimation (Kohl et al. 2006; Michael et al. 2008).

The aerial photographs were recorded on colour infrared (CIR) composition. Such a composition is chosen based on the fact that the photosynthetic activity of the vegetation has its maximum radiation reflectance in the near infrared from 700 to 950 nm (Lillesand et al. 2004).

CIR plays a key role in discriminating the tree species on the aerial photographs because it provides a diversity of multi-spectral information (Ross 1970). Because of the variations in the photosynthesis patterns, the radiation reflectance on the aerial photograph tends to be different on various types of growing vegetation thus enabling us to distinguish between tree species (Ross 1970).

Remote sensing technology and in particular the use of aerial photography, in the last decades has proven to be very effective in forest management applications such as forest inventory or forest monitoring. Furthermore it has significantly enhanced our ability to improve the inventorying of mountain forests. A great deal of credit can be ascribed to the incorporation of the DTM (Digital Terrain Model) with the aerial photographs which has a great influence on the accuracy of tree height measurements and subsequently on the overall volume estimation results (Baltsavias 1999; Hyypä and Hyypä 1999).

The aim of this study was:

- to elaborate and develop existing methods used in inventorying lowland forests and adapt them for mountainous forests,
- to increase efficiency and precision to provide reliable forest inventory data which are comparable and consistent,
- to further develop methods and analysis techniques to facilitate the use of aerial photographs for estimating the biophysical forest attributes.

## MATERIAL AND METHODS

### Mountainous forests

Around 20% of all forest in Europe are mountain forests and there is an increase awareness of the management and assessment of these forest ecosystems (EOMF 2000).

Naturally, mountainous forests are associated with topographic variations and fluctuations resulting in unique landscapes. Generally the occurrence of forest communities changes depending on the elevation, slope and aspect consequently stimulating the prevalence of certain species (Gluck 2001).

Elevation which refers to the altitude of the stand above sea level, determines in particular the vertical distribution of the tree species. Slope is another attribute of mountainous forest which is strictly related to the variations of the terrain (e.g. hill top, hillside, plain, valley, ridge, etc). Aspect on the other hand refers to the geographical orientation of the hill-slopes, in other words the direction which the forest stand is facing (e.g. east, west) and affects the horizontal tree species distribution (Jin et al. 2008).

The study area was the Stołowe Mountains National Park (Stołowe Mts NP) which is located in south-west of Poland. Stołowe Mountains National Park is composed of different forest stands, where spruce stands dominate among the others. From the total forest area of 5,671.8 hectares Norway spruce (*Picea abies* L.) stands represent more than 80% (Jędruszczak and Miścicki 2001). There are other tree species considered as the ruling species like Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), silver fir (*Abies alba* Mill.), European beech (*Fagus sylvatica* L.), sycamore (*Acer pseudoplatanus* L.) and birch (*Betula pendula* Roth. and *B. pubescens* Ehrh.). However often the area which they occupy is rather low, because the only tree species whose share exceeds 5% except spruce is beech, the other tree species share vary from 0.1 to 5%.

Two-phased method, as the term implies is characterised by two phases. In the 1<sup>st</sup> phase data are collected from two samples of the same population. In the 1<sup>st</sup> sample which is represented by the aerial plots, the

<sup>1</sup> “Stołowe” in Polish means “table-like” therefore Stołowe Mountains stands for Table Mountains referring to the shape of these mountains

auxiliary variables (e.g. crown cover, tree height, density) are measured whereas in the 2<sup>nd</sup> sample the variables of interest (e.g. DBH, tree height, age) are recorded during the terrestrial survey. The intent is to establish a statistical relationship between the auxiliary variables and the variables of interest by means of linear regression (Kohl et al. 2006). In the 2<sup>nd</sup> phase, using auxiliary variables which were chosen based on the calculations carried out in the 1<sup>st</sup> phase, an extended population of sample plots are measured. Afterwards variables of interest (e.g. standing volume) were computed by exploiting the regression estimators derived from the 1<sup>st</sup> phase and results of the 2<sup>nd</sup> phase.

The mean value is calculated for the inventory unit according to formula given by (Loetsch and Haller 1964).

$$\bar{v} = \bar{v}_N + b_{vx} (\bar{x}_1 - \bar{x}_2) \quad (1)$$

where:

$\bar{v}_N$  – mean value calculated from terrestrial measurements in phase I,

$b_{vx}$  – the slope coefficient between  $v$  (measured on the ground plots) and  $x$  (measured on the aerial plots) computed from the phase I,

$\bar{x}_1$  – mean value calculated from all aerial sample plots (phase I + II),

$\bar{x}_2$  – mean value calculated from the aerial sample plots of phase I.

Slope coefficient is calculated:

$$b_{vx} = \frac{r \cdot S_{vy}}{S_x} \quad (2)$$

where:

$r$  – correlation coefficient,

$S_{vy}$  – covariance characteristics of  $v$  and  $y$ ,

$S_x$  – standard deviation of  $x$ .

In order to determine the square of the standard error of mean value  $S_v^2$  following equation of Khan and Tripathi (1967) was used:

$$S_v^2 = \frac{s_v^2 (1 - R^2)}{n_2} \cdot \left( 1 + \frac{n_1 - n_2}{n_1} \cdot \frac{p}{n_2 - p - 2} \right) + \frac{R^2 \cdot s_v^2}{n_1} - \frac{s_v^2}{N} \quad (3)$$

where:

$S_v^2$  – variance of the variable of interest in the first phase,

$R^2$  – coefficient of determination,

$p$  – number of used variables,

$N$  – population size,

$n_1$  – size of the aerial sample plot (Phase I),

$n_2$  – size of the ground sample plot (Phase II).

### Measurement of ground sample plots

The terrestrial measurements were performed during July 2009 by the team of TAXUS SI. Measurements on the terrain consisted on a set of 355 circular permanent sample plots with a radius of 12.62 m. Permanent circular sample plots were distributed in a systematic grid arrangement each 400 meters on the entire area of the Stolowe Mts NP. From these plots the ground reference data were collected and afterwards the necessary analysis and calculations were undertaken to estimate the ground volume.

### Acquisition of aerial photographs

Before the acquisition of the images one of the most important steps is to determine the image scale. The scale depends on the objective and the accuracy requirements. In this study photogrammetric data were composed of 12 strips of aerial photo stereo pairs acquired on 03/07/2008 by SWISS Photo Company.

Digital images referred as photographs were acquired at a scale of 1:10000. The images were captured by airborne with a Vexcel UltraCam D camera using objective with a focal length 101.4 mm which registered four channels: B, G, R and IR. In this study CIR composition was used and spatial resolution of the images amounted a nominal pixel size of 13 cm. The aerial photographs were taken at an altitude of 2100 metres above sea level with a side lap 60% and end lap 30%.

### Preparation of aerial imagery for photogrammetric measurements

The interpretation of the aerial photography is based on the photogrammetric procedures which are executed by using “DEPHOS” digital photogrammetric software. During the process of the analysis and observation pairs of aerial photographs with stereoscopic overlap areas, which can be perceived in a three dimensional format, have been analysed and interpreted based on a scale of 1:10000. In this study the used coordinate system was PUWG 1992.

## Measurements of aerial sample plots

### Tree species identification and composition

Different tree species are associated with various intensities of reflection which has an influence on the colour, tone and texture of the aerial photographs. This difference allows to distinguish between tree species, however the difference among coniferous species or among deciduous is more subtle than in case of coniferous versus deciduous.

It is important for interpretation to achieve CIR photographs as close as possible to the typical one and to amplify features of observed objects. For this reason LUT (Look up Table) in DEPHOS was used.

After identifying all tree species which compose the plot, the second task is to estimate tree species composition. Tree species composition is expressed in percentage and represents the share within the plot which ranges from 1–100%. It should be noted, however, that the estimation could vary among different observers. Alternating between the observation of aerial photographs and forest stand maps of the study area has improved tree species classification.

### Tree height measurement

Tree height is one of the key parameters in forest inventory and can accurately be estimated from the aerial photographs (Duvenhorst 1995). Tree height measurements on the ground are considered to be more difficult and time consuming than measuring the DBH, especially in dense deciduous stands where sometimes it is impossible to see the top of the tree. Therefore retrieving tree heights from aerial measurements is of great advantage in accelerating the process of forest inventory.

Tree height is represented or is obtained by the difference of tree top and the terrain elevation at the base of the tree. The procedure goes as follows: once the tree of interest is located by placing the 3D cursor on the assumed tree apex (z-tree-top) its position is recorded (x,y,z coordinates). The coordinates at the base of the tree correspond with the ground elevation ( $z_{ground}$ ) from the DTM (Digital Terrain Model). Therefore subsequently the height of the tree is attained as the result of the subtraction of ground elevation from the (z) coordinate of the tree apex.

The average plot height was obtained from the share of average height of each tree species within the plot (eq. 4).

Average plot height

$$Avg\_Height = \frac{\text{Share of each tree species in \%} \times \text{average height of each tree species}}{100} \quad (4)$$

Height reduction was applied in order to avoid the estimation of the non merchantable volume. Trees as high as 7 meters do not produce assortments which could be considered merchantable therefore such trees are not inventoried during the field survey.

### Density measurements

Average density is one of the parameters which is derived from the measurements on the aerial photographs and is one of the variables which might have been used for the further calculations of the standing volume. On each plot are measured 6 distances between the six closest neighbours from the tree which is located closest to the centre plot. In case when there are not enough trees within the plot the measurements can take place outside the plot.

The formula used to calculate the average density is displayed below:

Average Density

$$D = \frac{12\ 200}{\left( \frac{L_1 + L_2 + \dots + L_6}{6} \right)^2} \quad (5)$$

where:

$D$  – average density,  
 $L_1 + L_2 + \dots + L_6$  – distances between the trees.

Density is expressed in trees  $ha^{-1}$ , and by multiplying the average height with the density another parameter was obtained such as “Sum of heights”.

Sum of heights

$$Sum\ of\ heights = avgheight \times density \quad (6)$$

where:

$avgheight$  – average height at plot level,  
 $density$  – average density at plot level.

Sum of heights is a variable used in building up the model for the estimation of the standing volume.

### Crown cover estimation

The crown cover of a sample plot is determined as the percentage of the area which is covered by the crowns vertical projection of the dominant and co-dominant trees in a given plot.

Basically this can be estimated through either 2D or 3D observation and the estimation might differ slightly from one observer to another. The percentage of the crown coverage is dependent on the tree density, age, tree species (in case of shade tolerant species it might be more dense) and tree species composition. Crown cover is an important feature in describing the horizontal stand structure.

### GREEN VOLUME CALCULATION

“Green volume” was calculated for each tree species and was derived as a sum of multiplication between average plot height, crown cover and the share of the particular tree species.

Calculation of green volume for particular species

$$GV = avg\_height \times CC\% \times tree\_species\% \quad (7)$$

where:

*avg\_height* – plot average height,  
*CC%* – plot crown coverage,  
*tree\_species%* – share of particular tree species within the plot.

Total green volume for the plot was calculated as a sum of the volume of each tree species present in the sample plot. Green volume at this stage represents the imaginary cylinder with a base diameter equal to the tree trunk diameter, therefore it has to be corrected.

### Age estimation

Age is a very informative attribute about the forest, and it can be either taken from the available forest management reports or determined through counting the annual rings of the trees. In case of aerial sample plots it was checked whether age given in the stands description corresponded with the height of trees and its crown diameter.

### Ground volume calculation

Standing volume is one of the most important attributes of the forest and it is a parameter of a great interest from the forest management and planning point of view.

Tree volume was a function tree DBH, tree height and volume coefficients of a particular tree species. Ground volume was calculated based on the measurements from the field investigation and was calculated for each inventoried individual tree. Plot volume was derived as a sum of the individual trees within the plot and extrapolated for the extended area. The volume for each tree species was calculated by using the formula *Schumacher-Hall* (Loetsch et al. 1973):

Ground volume calculation

$$V = 10^{a+b \log d_{1.3} + c \log h} \quad (8)$$

where:

*a, b, c* – coefficients which are depended on the tree species and the age group,  
*d<sub>1.3</sub>* – DBH (diameter at breast height),  
*h* – tree height.

Coefficients *a, b* and *c* used in Schumacher-Hall's volume equation for each tree species and corresponding age groups were based on the yield tables (Grudner and Schwappach 1952).

Results obtained from the ground measurements were used as reference data and also as construction part in the development of regression models, particularly ground volume.

### Calculation of variables on aerial sample plots

During the aerial measurements three sets of variables were computed. The first set of variables was derived from the direct measurements e.g. height, crown cover, average distance between trees, elevation. Belonging to the same set additional variables were computed e.g. average height, sum of heights, trees density, green volume. Second set of variables was derived from the multiplication of the variables of the 1<sup>st</sup> set, all variables were squared up producing new variables (e.g.  $CC\%^2$ ,  $avg\_height^2$ ,  $Green\_vol^2$ ). Third set of the variables was a combination of first and second variable set e.g. ( $CC\% \times Av\_Height$ ), ( $Elevation \times Height$ ), ( $Green\_vol^2 \times Density$ ).

### Calculation of the relationship between ground and aerial variables

By using correlation analysis we observe what the association between several variables individually and collectively is and later use them in multiple regressions. All correlation are described in a  $14 \times 14$  correlation matrix (Tab. 1).

What can be pointed out is a high positive relation between AH and Green\_Vol (0.85) and AH and Age (0.60). Furthermore it could be mention that a negative relationship exists between AH and Elevation ( $-0.56$ ), due to the fact that species show less height growth by rising up the altitude. Since all the variables are considered statistically significant they can be used in building up the regression model in order to derive estimators which will be used in predicting the standing volume.

Multiple regression models were built to generate equations in order to relate the parameters derived from the measurements on aerial sample plots (e.g. tree height, crown cover, density, green volume and elevation) and volume derived from the ground plots.

Multiple regression analysis was used to find the best fitting model for predicting standing volume. Different models were tested in order to determine parameter's values of various functions based on the data set where ground volume was the dependent variable.

### Measurement of the extended part of aerial sample plots

In the 2<sup>nd</sup> phase measurements were carried out on 2772 aerial plots distributed on the entire area of Stołowe Mountains National Park. During this phase only a few selected parameters were measured, unlike the 1<sup>st</sup> phase. The selection of the parameters to be measured was determined based on the regression model which was used to estimate the volume in the 1<sup>st</sup> phase. The variables of interest which were measured on the aerial photographs in the 2<sup>nd</sup> phase were selected based on their influence in final regression model. The auxiliary variables with no strong influence on the statistical relationship were excluded and not measured in the 2<sup>nd</sup> phase.

Volume computations for the plots measured in the 2<sup>nd</sup> phase were done by using the regression model which was developed from the combination of the auxiliary variables and variables of interest in the 1<sup>st</sup> phase.

### Variants of inventory with the use of aerial photographs

Once the volume was computed for each plot of the entire population in the Stołowe Mts NP, these plots were stratified into age classes. Computations of standing volume were carried out for each age class by using three different inventory approaches:

- aerial method (two-phased method),
- classical ground method and
- combined method.

**Tab. 1.** Correlation coefficients between the main variables which is described by the  $14 \times 14$  correlation matrix. With: AH – Average height; Elevation – Elevation of the sample plots; Age – Species-specific average age; Green\_Vol – species-specific predicted green volume; N – number of plots. \*\*. Correlation is significant at the 0.01 level (2-tailed)

Variables	Parameters	Variables			
		AH	Elevation	Age	Green_Vol
AH	Pearson Correlation	1	$-0.506^{**}$	$0.600^{**}$	$0.850^{**}$
	Sig. (2-tailed)		0.000	0.000	0.000
	N	355	355	355	355
Elevation	Pearson Correlation	$-0.506^{**}$	1	$-0.250^{**}$	$-0.527^{**}$
	Sig. (2-tailed)	0.000		0.000	0.000
Age	Pearson Correlation	$0.600^{**}$	$-0.250^{**}$	1	$0.461^{**}$
	Sig. (2-tailed)	0.000	0.000		0.000
Green_Vol	Pearson Correlation	$0.850^{**}$	$-0.527^{**}$	$0.461^{**}$	1
	Sig. (2-tailed)	0.000	0.000	0.000	



When using aerial inventory method, the volume for each age class is computed based on the same methodology as for the entire population (two-phased method), taking into account the surface unit. Accordingly computations and statistical tests were performed to determine mean volume, coefficients ( $R$ ,  $R^2$ ,  $b$ ), standard and relative errors.

Before applying of combined method, an analysis of covariance was used to compare the slope coefficient ( $b$ ) between particular age classes. The corresponding coefficients for each age class are switched for a common coefficient derived from the whole population (all age classes together). This is done in order to avoid the big differences among age classes within the allowed range. Practically the critical value of  $F$ -coefficient should not exceed 1.55 and in our case it was 1.066 therefore we were allowed to apply a common coefficient  $b = 1.029$  which represented the slope degree. Note, when using combined method in volume computation, volume is estimated with some error, therefore can be used only for comparison not as a standard method.

In the classical inventory method, for each individual tree species volume is calculated based on the formula of Schumacher-Hall (see Equation 9) and afterwards summed up at a plot level. Stratification into age classes has been applied only for permanent ground plots.

Statistical tests at  $P = 0.05$  significance level were run to verify and examine the accuracy of the three methods in order to determine their performance.

## RESULTS

### Relationship between ground and aerial variables

The selected model is a combination of the independent variables such as logarithmic Average height, logarithmic Green volume, and the square of the Green volume with Ground volume as dependent variable. Logarithmic method was used in order to avoid negative values because it would not make sense to have negative tree standing volume.

Volume calculation (Model 3)

$$Y = -1.412 + 0.220 \times AH\_log + 2.108 \times Green\_log - 0.258 \times Green\_V^2 \quad (9)$$

where:

- $Y$  – estimated volume,
- $AH\_log$  – logarithmic Average height,
- $Green\_log$  – logarithmic Green volume,
- $Green\_V^2$  – the square of the Green volum.

Regression models were compared to each-other for their statistical parameters (e.g.  $R^2$ ,  $R^2_{adj}$ , residual of mean squares) and their simplicity. There are a few criteria which are used to compare regression models found in literature. They are: coefficient of determination  $R^2$ , the larger the value the stronger is the relationship. Adjusted determination coefficient ( $R^2_{adj}$ ) is more comparable if the models are built by different numbers of variables. Residual of mean squares (MSE) is another criterion, a model with smaller MSE is more preferable. However  $R^2_{adj}$  and MSE quite often infer the same conclusion (Rawling 1988).

Tab. 2 summarizes the results derived from 3 regression models. Based on the criteria mentioned above, 3<sup>rd</sup> model was selected to predict the volume because it provided almost the same accuracy and it was built with less variables than the rest of the models. The idea behind is to reduce the time which is required to measure these variables on the aerial photographs. The difference in accuracy between the 3<sup>rd</sup> model and the other two was negligible.

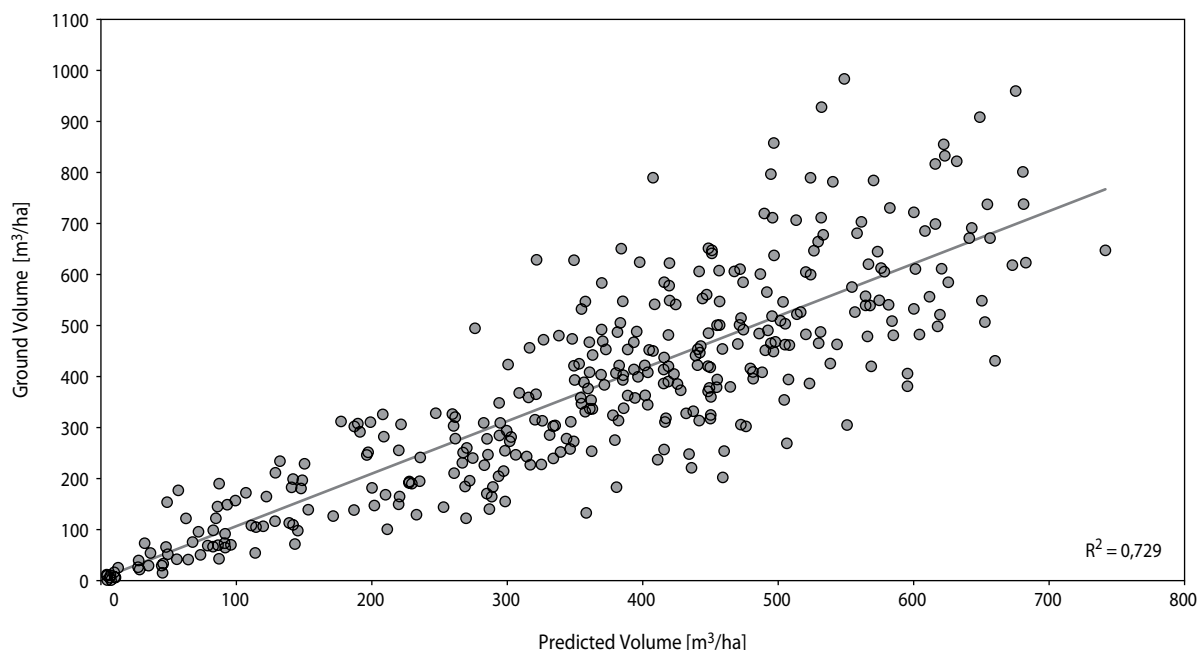
**Tab. 2.** Comparison of the best regression models selected for the prediction of standing volume. Models were examined based on their statistical parameters e.g. determination coefficient ( $R^2$ ), adjusted determination coefficient ( $R^2_{adj}$ ), residual of mean squares (MSE) at a significance level \*

Model	Auxiliary Variables	$R^2$	$R^2_{adj}$	MSE	Significance
1	Green_Vol; Age_GreenV; AH_Green; Elev_AH	0.747	0.745	11.232	< 0.001
2	Green_Vol; Age_GreenV; AH_Green;	0.746	0.744	11.273	< 0.001
3	AH_log; Green_log; Green_V <sup>2</sup>	0.726	0.724	11.184	< 0.001

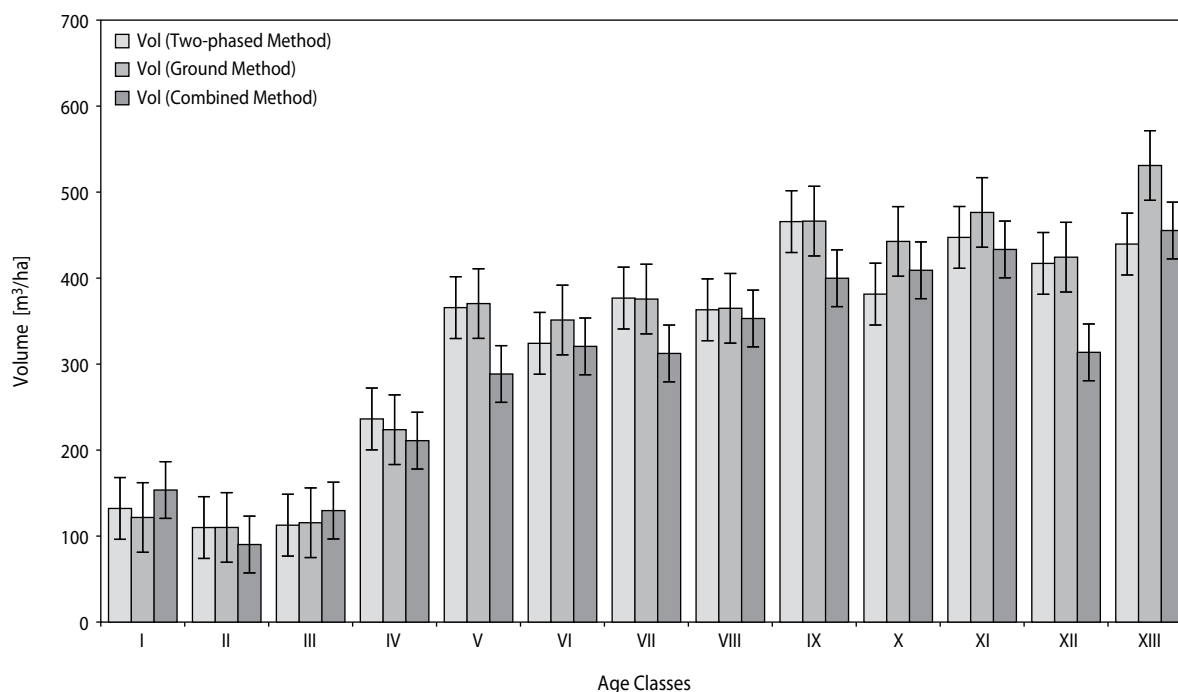
The use of the regression model built from the combination of average height, green volume and squared green volume revealed a high correlation and a linear

relationship. The coefficient of determination amounts to  $R^2 = 0.729$ , whereas the coefficient of multiple cor-

relation  $R = 0.852$  indicating a quite high relationship and efficient variable estimator selection. Results of the



**Fig. 1.** Correlation between ground volume and predicted volume



**Fig. 2.** Average standing volume for all age classes in forested area of Stołowe Mts NP, calculated by two-phased, ground and combined method (bars represent confidence limits CI at  $P = 0.05$ )



correlation between (ground volume) and (predicted volume) derived from the aforementioned model are plotted in Fig. 1.

### Standing volume in age classes and National Park

Standing volume was computed for each age class by using three methods and a comparison of the results is illustrated in the Fig. 2.

By the examination of the results (Fig. 2) it was observed that there was an underestimation of the volume from the aerial photographs for the old stands over 90 years, especially stands over 141 which show the highest difference.

The average volume for all age classes calculated by contemporary ground method produced the following results  $421 \pm 15 \text{ m}^3 \text{ ha}^{-1}$  and a relative error 3.6% at  $P = 0.05$  statistical significant level whereas two-phased method was quantified to  $403 \pm 11 \text{ m}^3 \text{ ha}^{-1}$  (i.e. 2.8%). Combined method on the other hand  $370 \pm 13 \text{ m}^3 \text{ ha}^{-1}$  (i.e. 3.5%). We can see that generally there is an underestimation of the volume when using the combined method especially in comparison with ground method.

The average volume for all stands without dividing them into age classes calculated by two-phased method was  $339 \pm 13 \text{ m}^3 \text{ ha}^{-1}$  (i.e. 3.9%).

Tab. 3 gives insights about the age classes with the corresponding mean volume, number of plots measured on the aerial photographs, on the ground and for the entire data set (3127 plots).

The correlation coefficient  $R$  for stands from 1–60 years old ranges not in a specific order from 0.736 to 0.967, whereas for middle aged stands 60–100 the value of  $R$  coefficient ranges from 0.628 to 0.913, and for stands over 100 years old the achieved  $R$  value was rather higher than the previous ones ranging from 0.773 to 0.913. However, the mean correlation coefficient  $R$  had a value 0.852 which indicates a high relationship between ground and aerial volume.

## DISCUSSION

The importance of this study firstly lies on the fact that by implementing two-phased method using aerial photographs and terrestrial sample plots the whole forested

**Tab. 3.** Mean volume predicted by two-phased method, number of ground and aerial plots for each age class unit in the territory of Stołowe Mts NP

Total no of aerial plots	Reduced no of aerial plots	Plots measured on the ground and air-photo	Age classes	Mean volume [ $\text{m}^3 \text{ ha}^{-1}$ ]	Cor. coefficient $R$
60	51	9	I	153	0.926
43	37	6	II	90	0.967
175	154	21	III	125	0.716
212	184	28	IV	211	0.785
213	192	21	V	207	0.736
306	269	37	VI	335	0.775
151	133	18	VII	321	0.628
309	266	43	VIII	351	0.835
539	484	55	IX	395	0.819
237	211	26	X	409	0.913
511	456	55	XI	429	0.773
271	245	26	XII	344	0.816
100	90	10	XIII	451	0.937
3127	2772	355	–	403	0.854

$R$  – linear correlation coefficient between the standing volume calculated on the permanent ground control plots and on aerial sample plots.

area of Stołowe Mts NP was inventoried. The accuracy was similar to the result of inventory for the management planning (carried on ground plots only – approx. 800 plots). Secondly, it proved that aerial photography could be applied practically in inventorying the mountainous forests and yield good results. Thirdly, the incorporation of DTM with the aerial photography has an enormous effect on the overall results especially regarding to height measurements, more so when we dealing with mountainous forests.

The results of this study are comparable with results achieved in other similar previous European studies which used different regression equations in predicting the standing volume. Ranked chronologically can be mentioned results from Stellingwerf (1962) who had conducted the measurements over 50–70 years old pine stand ( $R = 0.921$ ); Bogyay (1970) over 10–60 years old pine stand ( $R = 0.96$ ); Akca et al. (1997) achieved an ( $R = 0.847$ ) over mixed stands of spruce and beech. The most current study to which the results of these study are relevant in comparison is Miścicki (2009),  $R = 0.868$  whose study was conducted likewise this study over a mixed forested area. Needless to say the results from the other studies are slightly higher than the ones from the current study. The reason for this difference is the fact that the measurements in these studies were conducted mainly over stands with one dominant tree species except Miścicki (2009), whereas the current study comprised a forested area with various tree species and different ages. Therefore the results are considered as reliable and comparable with the highest results found in the literature.

## CONCLUSIONS

- The overall results indicate that CIR aerial photography may be used efficiently in inventorying the mountainous forests.
- Statistical analysis indicates that there were no statistically significant differences in mean values, calculated for all age classes when using both methods (two-phased method and classic ground method).
- Tree height was one of the parameters which was measured accurately and was identified as one of the key parameters in calculating the standing volume.

- Tree height and green volume were in particular the most important variables in generating the final regression model, which was used in estimating the standing volume.

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